Measurement of Parity Nonconservation in the Proton-Proton Total Cross Section at 800 MeV

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We report a measurement of parity nonconservation in the transmission of 800-MeV longitudinally polarized protons through an unpolarized, 1-m liquid-hydrogen target. The dependence of transmission on beam properties was studied to measure and to correct for systematic errors. The measured longitudinal asymmetry in the total cross section is $A_L = [+2.4 \pm 1.1(\text{statistical}) \pm 0.1(\text{systematic})] \times 10^{-7}$.

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We report the results of an experiment that searched for parity nonconservation (PNC) in the scattering of 800-MeV longitudinally polarized protons from an unpolarized hydrogen target. PNC arises from an interference between the strangeness-conserving weak interaction and the strong interaction and results in a change in the total cross section when the helicity is reversed. The longitudinal asymmetry A_L is defined as $A_L = (\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-)$, where σ_+ (σ_-) is the total cross section for positive- (negative-) helicity protons on the target.

Previous experimental results and theoretical treatment of PNC in nucleon-nucleon scattering give an incomplete picture of the energy dependence of the effect. Measurements[1-3] of A_L in p_{pol}-p scattering at 15 and 45 MeV have yielded small nonzero values of $A_L = (-1.7 \pm 0.8) \times 10^{-7}$ and $A_L = (-1.5 \pm 0.2) \times 10^{-7}$, respectively. Both low-energy results are in good agreement with theoretical predictions based on a meson-exchange model[4-6] and a hybrid quark model.[7] A high-energy experiment,[8] with 6-GeV/c protons on an H_2O target, has reported a value of $A_L = (+26.5 \pm 6.0 \pm 3.6) \times 10^{-7}$. This value is in agreement[9,10] with theoretical work based on quark-quark and wave-function renormalization[11] models, but it is more than an order of magnitude larger than predictions of meson-exchange models[12-15] for N-N scattering. Our group has recently reported[16] a measurement of $A_L = (+1.7 \pm 3.3 \pm 1.4) \times 10^{-7}$ for 800-MeV protons on an H_2O target. The 800-MeV work reported here is the highest-energy measurement of A_L for p_{pol}-p scattering to date, and it achieves a sensitivity in the measured value, $A_L = (+2.4 \pm 1.1 \ \pm 0.1) \times 10^{-7}$.

The experiment was performed with the Clinton P. Anderson Meson Physics Facility (LAMPF) polarized H^- beam. Polarized H^- ions were produced in a Lamb-shift–type ion source.[17] Neutral hydrogen atoms, initially polarized in the spin-filter region of the source, had their polarization reversed at 30 Hz by a weak magnetic field. Beam pulses were of 500-μs duration with a 120-Hz repetition rate. The proton-beam intensity ranged from 1 to 5 nA, and average polarization was 70%.

The layout of the apparatus is shown in Fig. 1. The transmission of protons through a 1-m-long liquid-hydrogen (LH_2) target was measured by two integrating ion chambers (I1 and I2), located upstream and down-

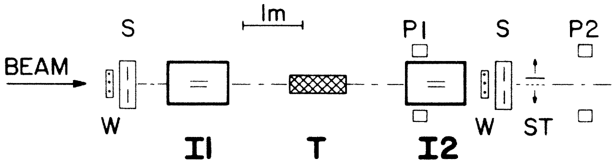

FIG. 1. Schematic of experimental setup. Ion chambers I1 and I2 measure the transmission of the liquid-hydrogen target T. Multiwire chambers W measure beam position and profile. Polarimeters P1 and P2, and CH_2 scanning-polarimeter target ST measure polarization. Beam position is servo stabilized by use of position signals from split-collector ion chambers S.

stream of the target. The statistical sensitivity of the measurement was limited by the available beam intensity as well as by detector noise due to nuclear spallation reactions in ion-chamber surfaces. To reduce the second effect, we developed and used spallation-minimizing ion chambers.[18]

For the two helicity states of the beam, the fractional change in transmission, Z, was determined from the analog difference of the I1 and I2 signals. This difference signal was amplified before digitization to reduce round-off error. For each group of four pulses the quantity $Z=(\overline{T}_+ - \overline{T}_-)/(\overline{T}_+ + \overline{T}_-)$ was calculated, where $\overline{T}_+$ ($\overline{T}_-$) is the average transmission for a pair of $+$ ($-$) helicity pulses. The helicity reversal pattern for the group of four pulses was $+ - - +$ to reduce the effects of drifts and to remove 60-Hz effects. At the end of a run, which consisted typically of 4×10^5 pulses, an average of Z was calculated and a statistical uncertainty was computed from the fluctuations of Z. The longitudinal asymmetry is $A_L = Z/(P \ln T)$, where P is the magnitude of the beam polarization and T is the average transmission of the target. For this experiment $P=0.7$ and $T=0.85$, resulting in a value of $1/(P \ln T)$ of -8.8. Hence to attain a sensitivity in A_L of 10^7, a measurement of Z with a sensitivity of nearly 10^{-8} was necessary.

Any characteristics of the proton beam that change when the helicity is reversed may affect the transmission measurement and give rise to a spurious PNC signal. We therefore monitored the beam position, intensity, size, and net transverse polarization (T_{pol}) for every pulse. In addition, the transverse-polarization distribution across the beam profile was sampled near the defining aperture (I2) to determine the first moment of transverse polarization across the beam profile (C_{pol}). A reversing T_{pol} induces a spurious PNC signal if the beam is displaced from the symmetry axis of the transmission detectors. A nonzero value of C_{pol} can result in an unwanted contribution to Z even if $T_{\text{pol}}=0$ and the beam is on the symmetry axis.[1,19]

The placement of the detectors that measure changes in beam properties is shown in Fig. 1. Integrating multiwire ion chambers,[20] W, monitored beam position and size for each pulse. Split-collector ion chambers, S, also monitored beam position and were part of a dual-loop feedback system that stabilized the average beam position and incident angle. A four-arm polarimeter, P1, used the LH_2 target as an analyzer to measure T_{pol} in the beam. A second polarimeter utilized a narrow target, ST, that continuously scanned the beam profile to measure C_{pol}. The upstream ion chamber of the transmission measurement recorded intensity variations of the incident beam.

To cancel contributions to A_L from beam changes uncorrelated to the beam helicity, the experiment was run for equal time periods in two different operating configurations (N and R) of the spin filter[17] in the polarized source. In both configurations protons exiting from the source were longitudinally polarized, but positive helicity for the N and R configurations occurred during opposite phases of the spin-flip field of the source. The combination $(Z_N - Z_R)/2$ measures the longitudinal asymmetry while canceling some systematic effects and is referred to as the PNC signal. The combination $(Z_N + Z_R)/2$, called HI, is expected to be 0 and serves as a test for unidentified systematic errors.

The final PNC and HI values of A_L are given in Table I. To correct Z for systematic contributions, its sensitivities to different systematics were determined. During the transmission measurement, the 30-Hz component of each beam systematic was monitored. Final corrections to Z were applied in the off-line analysis. Z values were corrected pulse by pulse for changes in beam intensity, position, and size. Corrections for T_{pol} were made for each group of four pulses, while corrections for C_{pol} and for unwanted electrical couplings were applied on a run-by-run basis. As a further test for unidentified systematic errors, the data

TABLE I. Values of longitudinal asymmetry, A_L, and of beam-systematic corrections in units of 10^{-7}. The errors in A_L and in the various corrections are not statistically independent.

		PNC			HI		
Quantity	Value	Statistical	Systematic	Value	Statistical	Systematic	χ^2 for 151 d.o.f.
A_L (uncorrected)	3.0	1.2		−5.0	1.2		301
Corrections to A_L:							
Position	−0.3	0.3	0.1	2.7	0.3	0.4	
Intensity	0.8	0.5	0.1	−7.7	0.5	0.8	
Size	−0.1	0.0	0.1	0.2	0.0	0.1	
Polarization	< 0.1	0.0	0.0	< 0.1	0.0	0.0	
C_{pol}	0.1	0.4	0.0	0.2	0.4	0.0	
Electrical pickup	0.0	0.0	0.0	−0.6	0.0	0.0	
A_L (corrected)	2.4	1.1	0.1	0.2	1.1	0.9	159
A_L (shift)	−0.7	1.1		−0.3	1.1		128

were analyzed for our using a shift in the four-pulse grouping that eliminates any helicity dependence from the calculated A_L. The resultant value, A_L (shift), was consistent with zero.

We discuss the systematic corrections in more detail:

(i) *Intensity.*—The sensitivity of Z to intensity modulations was determined with use of an apparatus[21] consisting of a set of stripper grids that were moved in and out of the H^- beam path to produce a 10% intensity modulation at 30 Hz. Stripper-grid data were taken as the dc intensity and size of the beam were varied. An analysis of these runs indicates a dependence

$$dZ/dI = A_0 + A_1 I + A_2 I^2 + A_3/\sigma_x + A_4 \sigma_y/\sigma_x,$$

where I is the beam intensity, σ_x (σ_y) is the horizontal (vertical) width of the incoming beam, and the A_i are coefficients determined from the data. The terms containing I result from nonlinearities in the detectors and electronics. The size-dependent terms are consistent with recombination effects within the chambers.

(ii) *Polarization.*—During the experiment, contributions from polarization systematics were minimized by locating the beam along the symmetry axis of the transmission detectors. To determine this axis, the transverse polarization was deliberately increased, and changes in Z were measured as the beam was scanned across I1 and I2. The position servo-loop system held the beam on the symmetry axis. As a result, transverse polarization gives the smallest of all systematic corrections: a correction to A_L of $< 1 \times 10^{-8}$.

(iii) *Position and size.*—At each transmission detector, position scans were performed to measure the sensitivity of Z to position. The largest measured sensitivity was $dZ/dy = 1.3 \times 10^{-4}$/ mm for vertical motion at the downstream detector. Small corrections for size variations were calculated from the quadratic components in the position dependence of Z. For approximately one third of all the runs the beam spot fell mostly on only two wires of the beam-size monitor, and hence the beam size could not be accurately determined. Size corrections were not applied for these runs. In the runs where size corrections were applied, their contribution to A_L was negligible.

(iv) C_{pol}.—Sampling of the transverse-polarization distribution by the polarimeter-scanning target was repeated continuously during a run. A full sampling cycle was completed every 2 min.

(v) *Unwanted electrical couplings.*—30-Hz electrical pickup was kept out of the difference signal in two ways. First, we used a 15-Hz digital signal to transmit the helicity-reversal information from the polarized source to the experiment. Second, optical or analog isolators were inserted in all important signal paths. Residual pickup contributions were measured in runs taken with the beam off.

Table I lists the corrections made to A_L for each systematic error. Applying the corrections improves the consistency of the data in several ways. First, within each run, corrected data have decreased pulse-to-pulse fluctuations in A_L. Figure 2 demonstrates that the correlations between Z and beam position and intensity are removed by application of the experimentally determined corrections. Second, when the data from all runs are tested for the hypothesis that the HI signal is 0 and that the PNC has a definite value, the χ^2 value for the corrected data is nearly a factor of 2 smaller than χ^2 for the uncorrected data. The corrected HI result is consistent with 0.

The measured parity-nonconserving longitudinal asymmetry is

$$A_L = [+2.4 \pm 1.1(\text{statistical}) \pm 0.1(\text{systematic})] \times 10^{-7}.$$

This result can be compared with a surprisingly large range of values among published predictions[22] for the asymmetry at 800 MeV. Calculations based on the model of meson exchange between nucleons correctly predict small, negative values of A_L at energies below 200 MeV. However, because the authors use different parametrizations of the strong nucleon-nucleon interaction, the predicted energy dependence of A_L above meson-production threshold shows a large var-

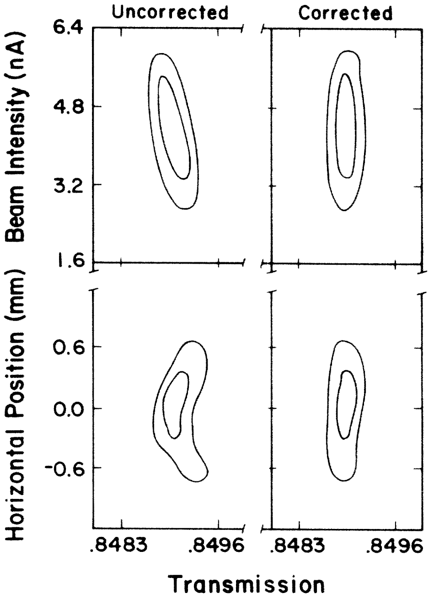

FIG. 2. Contours, at the 10% and 90% levels, of typical scatter plots displaying transmission vs intensity and vs horizontal beam position. Transmission values plotted in the scatter plots on the right are corrected for variations in position, intensity, and size. Comparison with the plots on the left, of uncorrected data, shows that application of the corrections removes the correlations.

iation. At 800 MeV the predicted values for A_L range from (-8×10^{-7})[14] to $(+3\times10^{-7})$[13] with intermediate values of (-0.2×10^{-7})[15] and $(+2\times10^{-7})$.[12] Additional values come from other models that have been used to calculate A_L at 800 MeV. A hybrid-quark model[7] predicts a value $\leq 1\times10^{-8}$, and the wave-function renormalization model,[23,24] predicts a large positive value $(+18\times10^{-7})$. If the high-energy quark-quark model[25] is extrapolated down to 800 MeV, the result is $+2\times10^{-7}$. No theoretical approach describes the energy dependence of p_{pol}-nucleon scattering at all energies. The meson-exchange approach can explain experimental results at energies up to 800 MeV, but underestimates the 6-GeV/c result. The QCD approach is consistent with the 6-GeV/c result as well as the 800-MeV experiment reported here, but is not applicable at low energies. Our experimental result provides a test that discriminates among the available predictions; it will also constrain future efforts to describe the energy dependence of A_L.

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